# A Bitter Pill: The Primordial Lithium Problem Worsens

Richard H. Cyburt

Joint Institute for Nuclear Astrophysics (JINA),

National Superconducting Cyclotron Laboratory (NSCL),

Michigan State University, East Lansing, MI 48824

Brian D. Fields

Departments of Astronomy and of Physics, University of Illinois, Urbana, IL 61801

Keith A. Olive

William I. Fine Theoretical Physics Institute,
University of Minnesota, Minneapolis, MN 55455, USA

## Abstract

The lithium problem arises from the significant discrepancy between the primordial  $^7\text{Li}$  abundance as predicted by BBN theory and the WMAP baryon density, and the pre-Galactic lithium abundance inferred from observations of metal-poor (Population II) stars. This problem has loomed for the past decade, with a persistent discrepancy of a factor of 2-3 in  $^7\text{Li}/\text{H}$ . Recent developments have sharpened all aspects of the Li problem. Namely: (1) BBN theory predictions have sharpened due to new nuclear data, particularly the uncertainty on  $^3\text{He}(\alpha,\gamma)^7\text{Be}$ , has reduced to 7.4%, and with a central value shift of  $\sim +0.04$  keV barn. (2) The WMAP 5-year data now yields a cosmic baryon density with an uncertainty reduced to 2.7%. (3) Observations of metal-poor stars have tested for systematic effects, and have reaped new lithium isotopic data. With these, we now find that the BBN+WMAP predicts  $^7\text{Li}/\text{H} = (5.24^{+0.71}_{-0.67}) \times 10^{-10}$ . The Li problem remains and indeed is exacerbated; the discrepancy is now a factor 2.4-4.3 or  $4.2\sigma$  (from globular cluster stars) to  $5.3\sigma$  (from halo field stars). Possible resolutions to the lithium problem are briefly reviewed, and key nuclear, particle, and astronomical measurements highlighted.

#### I. INTRODUCTION

Big bang nucleosynthesis (BBN) remains one of few probes of the early Universe with direct experimental or observational consequences [1]. Historically, BBN was generally taken to be a three-parameter theory with results depending on the baryon density of the Universe, the neutron mean-life, and number of neutrino flavors. Indeed, concordance between theory and observation for the abundances of the light elements, D, <sup>3</sup>He, <sup>4</sup>He, and <sup>7</sup>Li was a powerful tool for obtaining the baryon density of the Universe. Over the last twenty or so years, the number of light neutrino flavors has been fixed (in the Standard Model of particle physics) [2], and the neutron mean-life is measured accurately enough that it is no longer a parameter, but rather its residual uncertainty is simply carried into primarily an uncertainty in the predicted <sup>4</sup>He abundance (and is small) [2].

More recently, the baryon density has been determined to unprecedented accuracy by WMAP [3] to be  $\Omega_B h^2 = 0.02273 \pm 0.00062$  where  $\Omega_B = \rho_B/\rho_c$  is the fraction of critical density in baryons,  $\rho_c = 1.88 \times 10^{-29} h^2$  g cm<sup>-3</sup>, and h is the Hubble parameter scaled to 100 km/Mpc/s. This corresponds to a baryon-photon ratio of  $\eta_{10} = 6.23 \pm 0.17$  where  $\eta = n_B/n_{\gamma} = 10^{-10} \eta_{10}$ . This is significantly more accurate than any determination of  $\eta$  from observational determinations of light element abundances.

Thus the paradigm for BBN has shifted in the post-WMAP era [4, 5]. Nucleosynthesis is now a parameter-free theory. In the Standard Model, and working in the framework of a Friedmann-Robertson-Walker cosmology, the only inputs are the nuclear reaction rates (and their associated uncertainties). The last significant update to many of the needed rates was compiled by the NACRE group [6] and recent BBN calculations by several groups are in good agreement [7, 8, 9, 10, 11, 12].

What has emerged is rather excellent agreement between the predicted abundance of D/H as compared with the determined abundance from quasar absorption systems [13]. Indeed what is often termed the success in cosmology between BBN and the CMB is in reality only the concordance between theory and observation for D/H at the WMAP value of  $\eta$ . Currently, there is no discrepancy between theory and observation for <sup>4</sup>He. But this success is tempered by the fact that <sup>4</sup>He is a poor baryometer, it varies only logarithmically with  $\eta$ , and the observational uncertainty it rather large [14, 15].

It has also become generally accepted that there is a problem concerning the abundance

of <sup>7</sup>Li. At the WMAP value of  $\eta$ , the predicted abundance of <sup>7</sup>Li is approximately 3 times the observationally determined value. Several attempts at explaining this discrepancy by adjusting some of the key nuclear rates proved unsuccessful [9, 16, 17]. In fact, the key process for the production of <sup>7</sup>Li (in the form of <sup>7</sup>Be) is <sup>3</sup>He( $\alpha$ ,  $\gamma$ )<sup>7</sup>Be and has been remeasured recently by several groups [18] and one of the purposes of this paper is to explore the consequences of these new rates on the BBN production of <sup>7</sup>Li. At this time, it is unclear whether or not any known systematic effect may be responsible for the discrepancy or whether there is an indication of new physics at play.

In what follows, we will review the status of the  ${}^{3}\text{He}(\alpha,\gamma){}^{7}\text{Be}$  reaction rate and employ a new thermal fit to this rate. We will also briefly review the status of the  ${}^{7}\text{Li}$  observations as well as that of the other light elements. In section III, we will present the results of the BBN calculations using the new  ${}^{3}\text{He}(\alpha,\gamma){}^{7}\text{Be}$  rates and quantify the discrepancy with observations. In section IV, we discuss the remaining known alternative explanations of the discrepancy and we give our conclusions in section V.

#### II. NEW LIGHT ON THE LITHIUM PROBLEM

### A. BBN Theory: Updated Nuclear Data

The possibility of systematic errors in the  ${}^{3}\text{He}(\alpha,\gamma){}^{7}\text{Be}$  reaction, which is the most important  ${}^{7}\text{Li}$  production process in BBN, was considered in detail in [17]. The absolute value of the cross section for this reaction is known relatively poorly both experimentally and theoretically. However, the agreement between the standard solar model and solar neutrino data provides additional constraints on possible systematic shifts in this cross section. Using the standard solar model of Bahcall [19], and recent solar neutrino data [20], one can exclude systematic variations of the magnitude needed to resolve the BBN  ${}^{7}\text{Li}$  problem at the  $\gtrsim 95\%$  confidence level [17].

In order to maintain up-to-date nuclear input for BBN, several new efforts need to be addressed. In particular, the recent experiments measuring the neutron lifetime, evaluations of the  $p(n, \gamma)d$  and  ${}^{3}\text{He}(\alpha, \gamma){}^{7}\text{Be}$  data, and the resulting revisions to the  ${}^{3}\text{He}(\alpha, \gamma){}^{7}\text{Be}$  cross section and its error budget.

The new neutron lifetime measurement by [21] finds a lifetime,  $\tau_n = 878.5 \pm 0.8$ . This is

more than  $5\sigma$  away from the current world average  $\tau_n = 885.7 \pm 0.8$  recommended by the Particle Data Group [2]. Obviously, this points to unknown systematics between the experiments. Several possible explanations exist [22], but remain to be explored experimentally. We thus, follow the PDG'08 recommendation, until some understanding of the discrepancy can be found.

The  $p(n, \gamma)d$  determines at what point the deuterium bottleneck ends. Experimentally, this reaction is quite difficult to measure in the relevant energy range for BBN. We thus rely on theoretical-based cross-sections which are normalized to the existing experimental data. Several methods have been used to determine the shape of this cross section; microscopic potential models [23], R-matrix fits [24],  $N^4LO$  pion-less effective field theory [25], and NLO di-baryon effective field theory [26]. All methods agree well, though the R-matrix fit deviates by up to  $\sim 4\%$  from the others. Evaluating all the relevant data, np-scattering, deuteron ground state properties as well as the radiative capture and photo-dissociation data using a Markov Chain Monte Carlo algorithm, a best fit with propagated uncertainties [26], finds  $\lesssim 1\%$  errors in the capture rate. We adopt this rate in our network. The new rate is  $\sim 1\%$  higher than that adopted by [10] at  $E \sim 500$  keV.

At  $\eta_{\rm WMAP}$ , <sup>7</sup>Li is produced as <sup>7</sup>Be, and the only important reactions are production via <sup>3</sup>He( $\alpha, \gamma$ )<sup>7</sup>Be and destruction via <sup>7</sup>Be(n, p)<sup>7</sup>Li and subsequent <sup>7</sup>Li( $p, \alpha$ )<sup>4</sup>He. Of these, new developments in <sup>3</sup>He( $\alpha, \gamma$ )<sup>7</sup>Be experimental efforts [18], must be taken into account. The apparent discrepancy between prompt gamma-ray and <sup>7</sup>Be activation measurements discussed in [27] has virtually disappeared, though discrepancies between datasets still persist. A new evaluation [28], examines the "modern" data and finds a best fit and 68.3% CL uncertainties for a model independent fit, using a Markov Chain Monte Carlo algorithm similar to that of [26]. Special care is taken to properly propagate the dominating systematic normalization errors, as standard statistical treatments underestimate the true uncertainties. They find a zero-energy astrophysical S factor  $S_{34}(0) = 0.580 \pm 0.043$  keV b, an uncertainty of 7.4%. In the Gamow window ( $E \sim 200$  keV), this new fit gives a central value 17% higher than previous work [10].

Using the scalings provided in [10] (their Eqn. 47), the two new rates and baryon density, we expect an increase in the  $^{7}$ Li prediction to  $\sim 5.3 \times 10^{-10}$ . This increase combined with reduced errors will aggravate the Li problem as we show below.

## B. CMB Cosmological Parameters: Updated Baryon Density

As noted above, the major paradigm shift for BBN came with the first WMAP determination of the baryon density. The first year WMAP best fit, assuming a variable spectral index was [29]  $\Omega_B h^2 = 0.0224 \pm 0.0009$  which corresponds to a value of  $\eta$ :  $\eta_{10}(\text{WMAP2003}) = 6.14 \pm 0.25$ . This level of accuracy was already able to pin the light element abundances down to a narrow range.

The 5-year data WMAP data are consistent with their first year data, and the errors have been significantly reduced. The 5-year data give  $\Omega_B h^2 = 0.02273 \pm 0.00062$ , or

$$\eta_{10}(\text{WMAP2008}) = 6.23 \pm 0.17$$
(1)

We will adopt this value for the present study.

It is worth recalling key assumptions which enter into the inference of  $\eta$  from the CMB. The baryon density arises from the pattern of acoustic oscillations which modulate an underlying primordial spectrum of temperature perturbations (e..g., [30]). The baryon density inferred from CMB data thus depends on the nature of the primordial perturbation power spectrum, which is usually assumed (with motivation from inflation) to be a simple or running power law, close to the Harrison-Zel'dovich form. If the primordial power spectrum had a richer form, however, then the cosmological parameters inferred from the temperature anisotropies can be changed substantially [31]. Fortunately, the inclusion of precision polarization data, and their cross-correlation with the temperature data, goes far to independently characterize the primordial spectrum and to sharpen the precision of cosmic parameters. The launch of Planck in the next few months will offer just such precision determination of CMB polarization, and thus should further reduce the systematic and statistical uncertainties in the baryon density.

In using the WMAP value for  $\eta$  at the period of BBN, we are implicitly assuming that there has been no entropy change between BBN and the decoupling of the CMB. Note that entropy production between BBN and decoupling would require a *larger* value for  $\eta$  at the time of BBN and make the Li problem even worse.

## C. Stellar Lithium Observations: Updates, Systematics and Isotopic Ratios

There have been several recent observational determinations of the <sup>7</sup>Li abundance in metal-poor halo stars. Most observations lead to a <sup>7</sup>Li abundance in the range  $(1-2)\times 10^{-10}$ , consistent with the original determination by Spite and Spite [32]. Precision data have suggested a small but significant correlation between Li and Fe [33] which can be understood as the result of Li production from Galactic cosmic rays [34, 35]. Extrapolating to zero metallicity one arrives at a primordial value [36] Li/H|<sub>p</sub> =  $(1.23\pm0.06)\times 10^{-10}$ , though the systematic uncertainties were recognized to be large and an abundance of

$$(\text{Li/H})_{\text{p,field}\star} = (1.23^{+0.68}_{-0.32}) \times 10^{-10}$$
 (2)

was derived at 95% confidence.

There have been several measurements of  $^7\mathrm{Li}$  abundances in globular clusters. The abundance in NGC 6397 was measured by [37] to be

$$(\text{Li/H})_{p,GC} = (2.19 \pm 0.28) \times 10^{-10}$$
 (3)

Other groups found similar values of  $(1.91 \pm 0.44) \times 10^{-10}$  [38] and  $^{7}\text{Li/H} = (1.69 \pm 0.27) \times 10^{-10}$  [39]. A related study (also of globular cluster stars) gives  $^{7}\text{Li/H} = (2.29 \pm 0.94) \times 10^{-10}$  [40].

An important source for systematic error lies in the derived effective temperature of the star. [Li] =  $\log(^{7}\text{Li/H}) + 12$  is very sensitive to the temperature, with  $\partial[\text{Li}]/\partial T_{\text{eff}} \simeq 0.065$  – 0.08. Unfortunately there is no industry standard for determining effective temperatures, and for a given star, there is considerable range depending on the method used. This spread in temperatures was made manifest in the recent work of Melendez and Ramirez [41] using the infra-red flux method (IRFM) which showed differences for very low metallicities ([Fe/H] < -3) by as much as 500 K, with typical differences of  $\sim 200$  K with respect to that of [33]. As a consequence the derived  $^{7}\text{Li}$  abundance was significantly higher with  $\text{Li/H}|_{p} = (2.34 \pm 0.32) \times 10^{-10}$  [41, 42].

Recent observations of metal-poor stars do not find support for the large temperature scale in [41]. Using H- $\alpha$  wings Asplund et al. [43] found temperatures consistent with previous determinations using the IRFM. This work also showed a non-negligible correlation with metallicity leading to an estimate of the primordial <sup>7</sup>Li abundance between 1.1 and

 $1.5 \times 10^{-10}$ . A larger slope (with larger uncertainty) was also seen in [44] (also using H- $\alpha$  lines) in their study of extremely metal-poor stars. Because of the large slope seen in this data, the extrapolation to zero metallicity leads to a primordial <sup>7</sup>Li abundance of 8.72  $\pm 1.71 \times 10^{-11}$ , below that found in previous studies (though their mean value is consistent with other determinations).

A dedicated set of observations were performed with the specific goal of determining the effective temperature in metal-poor stars [45]. Using a large set of Fe I excitation lines ( $\sim 100$  lines per star), the Boltzmann equation was used with the excitation energies,  $\chi_i$  to determine the temperature through the distribution of excited levels. Again, there was no evidence for the high temperatures reported in [41], rather, temperatures were found to be consistent with previous determinations. The mean <sup>7</sup>Li abundance found in [45] was  $\text{Li/H} = (1.3-1.4\pm0.2)\times10^{-10}$ , consistent with the bulk of prior abundance determinations.

There are of course other possible sources of systematic uncertainty in the <sup>7</sup>Li abundance. It is possible that some of the surface <sup>7</sup>Li has been depleted if the outer layers of the stars have been transported deep enough into the interior, and/or mixed with material from the hot interior; this may occur due to convection, rotational mixing, or diffusion. Estimates for possible depletion factors are in the range ~ 0.2–0.4 dex [46]. Recent attempts to deplete the <sup>7</sup>Li abundance through diffusion introduce a source of turbulence tuned to fit the abundances of heavy elements in NGC6397 [47]. It is not clear whether this mechanism will work for the wide range of stellar parameters seen in the field. As noted above, the Li data show a negligible intrinsic spread in Li. Any mechanism which reduces significantly the abundance of <sup>7</sup>Li must do so uniformly over a wide range of stellar parameters (temperature, surface gravity, metallicity, rotational velocity etc.). At the same time, the mechanism must avoid the nuclear burning of <sup>7</sup>Li in order to preserve some <sup>6</sup>Li (which burns at a lower temperature).

In fact, not only does <sup>6</sup>Li challenge models of stellar depletion of <sup>7</sup>Li, but may require non-standard models to understand its abundance at low metallicity. Recent data [43] (though called into question [48]) indicates the presence of a plateau in <sup>6</sup>Li at the level of about 1000 times the BBN predicted <sup>6</sup>Li abundance [35, 49]. While this abundance of <sup>6</sup>Li can not be explained by conventional galactic cosmic-ray nucleosynthesis [34, 35, 50], it can be explained by cosmological cosmic-ray nucleosynthesis due to cosmic rays produced at the epoch of structure formation [51].

It is also possible that the lithium discrepancy (ies) is (are) a sign of new physics beyond

the Standard Model. One possibility is the cosmological variation of the fine structure constant. Varying  $\alpha$  would induce a variation in the deuterium binding energy and could yield a decrease in the predicted abundance of <sup>7</sup>Li [52]. A potential solution to both lithium problems is particle decay after BBN which could lower the <sup>7</sup>Li abundance and produce some <sup>6</sup>Li as well [53]. This has been investigated in the framework of the constrained minimal supersymmetric Standard Model if the lightest supersymmetric particle is assumed to be the gravitino [54] and indeed, some models have been found which accomplish these goals [55].

## III. THE LITHIUM PROBLEM QUANTIFIED

As discussed in section IIA, we have incorporated the new cross section measurements of  ${}^{3}\text{He}(\alpha,\gamma){}^{7}\text{Be}$  as well as an updated rate for  $p(n,\gamma)d$  into the BBN calculation of the light element abundance. Since the Li problem is our primary focus here, we first show the effect of the new rate determination for  ${}^{3}\text{He}(\alpha,\gamma){}^{7}\text{Be}$  [28] in Fig. 1. There, the primordial abundance of  ${}^{7}\text{Li}/\text{H}$  is plotted as a function of  $\eta$  or equivalently the baryon density,  $\Omega_{b}h^{2}$ , shown on the upper horizontal axis. The new result is shown by the green shaded region which is superimposed on top of the older result taken from [10] and shown shaded in red. The thickness of the bands corresponds to one sigma uncertainty in the calculated abundance as determined by a Monte Carlo simulation of the BBN reaction network. Also shown as a vertical yellow shaded band, is the one sigma range for  $\eta$  as determined by WMAP [3]. To highlight the change in the Li error budget, Fig. 2 shows the fractional uncertainty in Li/H as a function of  $\eta$ , for the same two sets of rates as in Fig. 1.

As expected, at low  $\eta$ , there is virtually no effect of the new rate for  ${}^{3}\text{He}(\alpha, \gamma){}^{7}\text{Be}$ , with essentially no change in the central value and fractional error of  ${}^{7}\text{Li}$ . However, at higher  $\eta$ , Fig. 1 shows a slight shift to larger values of  ${}^{7}\text{Li}/\text{H}$ . Most pronounced at high  $\eta$ , however, is the reduction the  ${}^{7}\text{Li}$  fractional error seen in Fig. 2, indicating a greatly reduced uncertainty in the BBN calculation. At the WMAP value of  $\eta_{10}=6.23$ , we find

$$^{7}\text{Li/H} = (5.24^{+0.71}_{-0.62}) \times 10^{-10}$$
 (4)

to be compared with the previous value of  $^{7}\text{Li/H} = (4.26^{+0.91}_{-0.86}) \times 10^{-10}$  [10]. The shifts in both the central value and the error range almost entirely reflect the corresponding shifts in

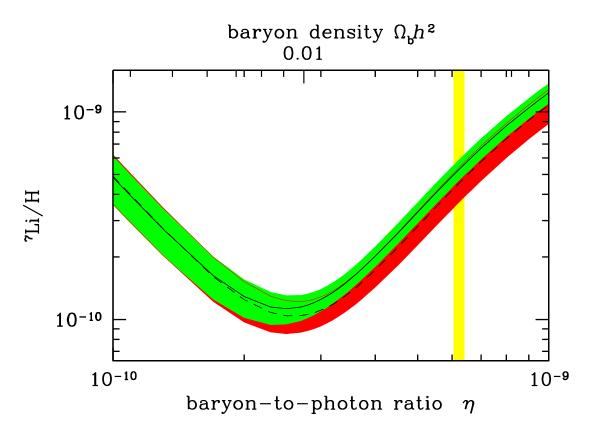


FIG. 1: A comparison of the  $^7\text{Li}/H$  abundances as a function of  $\eta$  using the new  $^3\text{He}(\alpha, \gamma)^7\text{Be}$  rate determined in [28] (green band) to the older result from [10] (red band). The thickness of the bands represents 1  $\sigma$  uncertainties in the calculated abundance. Central values are given by thick solid and dashed curves respectively. The thin upper curve (within the green shaded region) demarcates the border of the old result. The yellow vertical band is the WMAP value of  $\eta$  [3].

the  ${}^{3}\mathrm{He}(\alpha,\gamma){}^{7}\mathrm{Be}$  cross section and rate.

One may notice the difference between the baryon-density convolved value of  $^{7}\text{Li/H}=4.26\times10^{-10}~(\eta_{10}=6.14\pm0.25)$  and the fixed baryon density value of  $^{7}\text{Li/H}=4.36\times10^{-10}~(\eta_{10}\equiv6.14)$ . This  $\sim2\%$  shift is due to  $\eta$  dependence of the uncertainties in the  $^{7}\text{Li/H}$  prediction. With the higher precision year 5 WMAP baryon density, this shift is  $\lesssim1\%$ . The differences can be fully explained by the simple scalings from [10].

In [9], it was found that the adopted prescription for defining errorbars, underestimated the true uncertainty for the reaction  ${}^{3}\text{He}(\alpha,\gamma){}^{7}\text{Be}$ , due to the visible discrepancy between datasets. Therefore, a different method was used to evaluate this reaction's uncertainty (and only this reaction). Had this method been uniformly applied to all reactions, to account for

all discrepant or non-discrepant data, recognizing that the quoted errors are in fact minimum (not actual) uncertainties akin to the "minimal" errors discussed in [7], their prediction would still agree with the result in [10], but with inflated errorbars ( $^{7}\text{Li/H}=4.15^{+.49}_{-.45} \times 10^{-10}$ ).

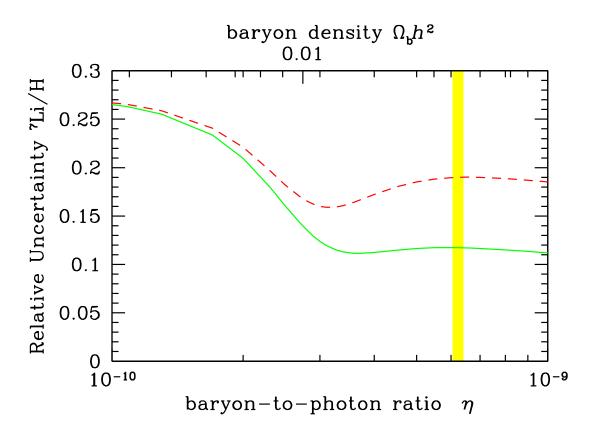


FIG. 2: The fractional error  $\sigma(\text{Li})/\text{Li}$  in the BBN lithium prediction, shown as a function of  $\eta$ . The solid curve is our result; the broken curve gives the older result from [10] as in Fig. 1. The yellow vertical band is the WMAP value of  $\eta$  [3].

The full set of light element abundances from BBN is shown in Fig. 3. The  ${}^{4}$ He abundance is plotted as a mass fraction as a function of  $\eta$  in the top panel. The thickness of the  ${}^{4}$ He band is primarily due to the small uncertainty in the neutron mean life. The D and  ${}^{3}$ He abundances by number with respect to H are shown in the middle panel, and the  ${}^{7}$ Li abundance (also by number) is shown in the lower panel. As one can see, the WMAP determination of the baryon density is precise enough, that one can now simply read off the predicted primordial abundances of the light elements. These are:

$$Y_p = 0.2486 \pm 0.0002 \tag{5}$$

$$D/H = (2.49 \pm 0.17) \times 10^{-5}$$
(6)

and

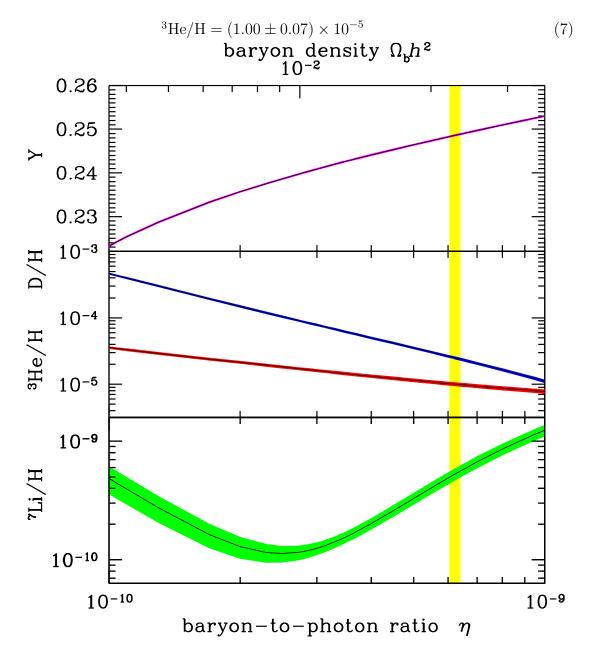


FIG. 3: The light element abundances of D,  ${}^{3}\text{He}$ ,  ${}^{7}\text{Li}$  by number with respect to H, and the mass fraction of  ${}^{4}\text{He}$  as a function of  $\eta$ . The thickness of the bands represents 1  $\sigma$  uncertainties in the calculated abundance. The yellow band gives the WMAP  $\eta$  [3].

The BBN predictions can be compared directly with current observational determinations of the light element abundances. The BBN likelihood functions can be defined by a convolution over  $\eta$ 

$$L_{\rm BBN}(X) = \int d\eta \ L_{\rm BBN}(\eta|X) \ L_{\rm WMAP}(\eta) \tag{8}$$

using the Monte Carlo results from BBN as a function of  $\eta$  to give  $L_{\text{BBN}}(\eta|X)$  and the WMAP value of  $\eta$  distributed as a Gaussian,  $L_{\text{WMAP}}(\eta)$ . These are shown in Fig. 4 by the dark (blue) shaded regions. Though there are useful measurements of the <sup>3</sup>He abundance [56], these are difficult to match to the primordial abundance [57]. We will show the BBN likelihood for <sup>3</sup>He in Fig. 4, but will not discuss <sup>3</sup>He any further.

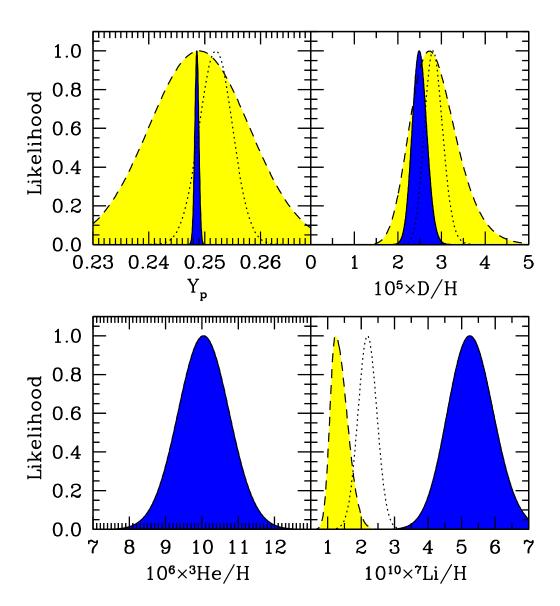


FIG. 4: The theoretical and observational likelihood functions for  $^4$ He, D/H,  $^3$ He/H, and  $^7$ Li/H. BBN results have been convolved with the WMAP determination of  $\eta$  and are shown as dark (blue) shaded area. The observational likelihoods are shown as light (yellow) shaded regions as well as alternative dotted curves. The data and distinctions are detailed in the text.

Fig. 4 also shows the observational likelihoods for comparison. For <sup>4</sup>He, the light (yellow)

shaded region corresponds to the result found in [14] using a select subset of the data in [58]. Systematic uncertainties and degeneracies in the set of physical parameters used to determine the helium abundance led to a value of Y extrapolated to zero metallicity of  $Y_p = 0.249 \pm 0.009$ . The mean value of the reanalyzed data is  $0.252 \pm 0.003$  and that is shown by the dotted likelihood function. Because of the large observational uncertainty in determining  $Y_p$ , both agree quite well with the accurate prediction made by BBN.

The deuterium abundance at low metallicity has been measured in several quasar absorption systems [13]. The weighted mean value of the seven systems with reliable abundance determinations is  $\log D/H = -4.55 \pm 0.03$  where the error includes a scale factor of 1.72 [2] and corresponds to  $D/H = (2.82 \pm 0.21) \times 10^{-5}$ . Since the D/H shows considerable scatter, it may be appropriate to derive the uncertainty using sample variance (see eg. [7]) which gives  $\log D/H = -4.55 \pm 0.08$  or  $D/H = (2.82 \pm 0.53) \times 10^{-5}$ . Both are shown plotted as log-normal distributions by the dashed curve (light shaded area) and dotted curve respectively in the D/H panel of Fig. 4. As one can see, there is very good agreement between the predicted and observationally determined value of D/H.

Finally, we come to <sup>7</sup>Li. The inferred primordial value from field halo stars (eq. 2) is shown by the light shaded area in the Li panel of Fig. 4. The slightly higher determination in a globular cluster (eq. 3) is shown by the dotted likelihood function. As one can see, the reduced uncertainty in the BBN prediction leads to virtually no overlap between the theoretical and observational likelihoods.

#### IV. EXPERIMENTAL AND OBSERVATIONAL STRATEGIES

We see that the cosmic lithium problem not only remains but has become even more pressing. As we have noted already, several proposed solutions to the Li discrepancy remain viable. Fortunately, the different scenarios proposed thus far can be ruled in (or out) empirically, both in the laboratory and in the observatory. Here we outline a strategy for doing so.

The most exciting possibility, in our opinion, is that the lithium problem points to new physics at work in the early Universe. This possibility could receive strong support—in the most optimistic case, nearly outright confirmation—by the discovery of new physics at the Large Hadronic Collider (LHC) at CERN, slated to start running in late 2008. The presence

of particle physics beyond the Standard Model would immediately cast the Li problem in a new light, since the correctness of the Standard Model is one of the key assumptions in the BBN calculation of Li and all of the light element abundances.

Consider, for example, the implications of the LHC finding evidence for supersymmetry (SUSY). This would place the highest priority on the study of SUSY effects on nucleosynthesis based on the potentially measurable sparticle spectrum. However, the fact that supersymmetry is realized in nature would not, by itself, guarantee a solution to the Li problem. This also requires that SUSY particles alter the light element abundances either during or after BBN. The lightest supersymmetric particle (LSP) would be stable and make up the weakly-interacting dark matter today, but its feeble interactions would also make it an inert spectator to nucleosynthesis. If, however, the next-to-lightest supersymmetric (NLSP) particle were relatively long lived ( $\tau \sim 1-1000$  sec or more) then its decays would release a cascade of Standard Model particles which would alter the light element abundances and potentially solve the Li problem [53, 54, 55]. Hence, the most direct laboratory signature of a SUSY solution to the Li problem would be the discovery of a long-lived NLSP.

In many of the cases studied [54, 55], the gravitino is the LSP and the partner of the tau lepton is the NLSP. Unfortunately, in the constrained versions of the minimal supersymmetric Standard Model, if these two sparticles make up the low mass end of the spectrum, obtaining lifetimes as short as  $\sim 1000$  s, would require a very massive spectrum beyond the reach of the LHC.

New astronomical observations of various kinds will play an important role in further sharpening the Li problem and probing its solutions. To date, metal-poor halo stars in our own Galaxy remain the only observational targets for determining the primordial Li abundance. Identifying and exploiting new sites for primitive Li detection, with different systematic issues, would offer crucial cross-checks on the halo star results. For example, metal-poor high velocity clouds probably represent the Galactic infall of the primitive intragroup medium of the Local Group. Li abundances in these clouds, seen in absorption against background quasars, would provide the first measures of extragalactic Li and with very deep exposures could even yield isotopic abundances, all without any issues of stellar evolution or atmospheric modeling [59]. An even more challenging but exciting possibility would be to observe highly redshifted lines from cosmic Li recombination [60]. This process occurs after the usual hydrogen recombination but still at  $z \sim 400-500$  and thus the Li features,

if measured, would probe not only the cosmic Li abundance before star formation began, but also give information about the universe in the "dark ages." Another observation which bears indirectly on the Li problem will be the new determination of the extragalactic gammaray background by the now-operational GLAST observatory; these data probe the non-cosmological but pre-Galactic Li contribution by cosmic rays in galaxies and on cosmological scales [51].

If and when new sites for Li determination become available, halo stars will nevertheless remain the dominant probe of primordial Li for some time to come. Thus there will remain a pressing need to understand systematics and to obtain abundance measures which are both precise and accurate. Further targeted, systematic studies of the kind outlined in §II C are of the highest importance. Moreover, robust <sup>6</sup>Li data are exceedingly important, as the mere existence of primordial <sup>6</sup>Li at currently observable levels immediately demands nonstandard nucleosynthesis, and the <sup>6</sup>Li/H abundance is a crucial constraint on all models. Even in the absence of primordial <sup>6</sup>Li, the inevitable component from Galactic cosmic-ray processes, and a possible contribution from cosmological cosmic rays, both provide unique and empirical means of subtracting the non-primordial <sup>7</sup>Li produced by these mechanisms.

Nuclear experiment and theory remain important inputs to the Li problem, but as noted above, it would seem that the few relevant reactions are by now well understood, and a nuclear solution to the Li problem is unlikely. That said, it is obvious that the discovery of a large and unknown systematic error would not only be surprising but could also dramatically affect the problem.

Finally, we note that these diverse experimental and observational arenas will contribute in complementary ways. As LHC probes of SUSY and other new physics rule particle solutions in or out, astronomical observations will sharpen the ability of Li and BBN to probe the solution space.

#### V. CONCLUSIONS

The first-year WMAP data determined the cosmic baryon-to-photon ratio  $\eta$  with a high precision that, in concert with BBN theory, predicts a primordial <sup>7</sup>Li abundance significantly above the levels inferred from the most metal-poor halo stars. In this paper we have revisited this cosmic lithium problem, which has seen important new contributions from nuclear

experiments, halo star observations, and the 5-year WMAP data. We find that the discrepancy is now a factor 2.4-4.3 or  $4.2\sigma$  (from globular cluster stars) to  $5.3\sigma$  (from halo field stars), which is largely due to the tighter errors on the baryon density and the  ${}^{3}\text{He}(\alpha, \gamma){}^{7}\text{Be}$  cross section.

A wide variety of possible solutions to the Li problem have been proposed. These range from observational systematics in determining halo star Li, to nuclear effects, to exotic physics beyond the Standard Model. Of these, nuclear physics solutions seem essentially ruled out at this point. Observational systematics remain a challenging problem and a possible solution, but the hope that a revised temperature scale in halo stars would significantly reduce the Li discrepancy is challenged by recent data which confirm the existing scale. The possibility that lithium points to new physics at work in the early universe thus remains not only viable, but if anything more likely.

Upcoming experiments and observations will help clarify the lithium problem and its solution. In particular, the LHC will probe particle physics Li solutions generally and supersymmetry in particular. These results will be complemented by a host of astronomical observations. *Planck* observations of the CMB, particularly polarization, will further nail down the cosmic baryon density. The first extragalactic Li abundances will offer an independent constraint on primordial Li with completely different systematics than halo stars. And finally further halo star measurements, focusing on systematics and on <sup>6</sup>Li, will remain crucial in quantifying the Li discrepancy from standard BBN and probing the mechanism which resolves this disagreement.

R.H.C is supported through the NSF grant PHY 02 16783 (JINA). The work of KAO was partially supported by DOE grant DE-FG02-94ER-40823.

T. P. Walker, G. Steigman, D. N. Schramm, K. A. Olive and K. Kang, Ap.J. 376 (1991) 51;
 K. A. Olive, G. Steigman, and T. P. Walker, Phys. Rep. 333 (2000) 389.
 B. D. Fields and K. A. Olive, Nucl. Phys. A777, 208 (2006);
 B. D. Fields and S. Sarkar, J. Phys. G33 (2006) 220;
 G. Steigman, Ann. Rev. Nucl. Part. Sci. 57, 463 (2007).

<sup>[2]</sup> C. Amsler *et al.*, Physics Letters **B667**, 1 (2008).

<sup>[3]</sup> J. Dunkley et al. [WMAP Collaboration], arXiv:0803.0586 [astro-ph].

- [4] R. H. Cyburt, B. D. Fields and K. A. Olive, Astropart. Phys. 17 (2002) 87 [arXiv:astro-ph/0105397].
- [5] R. H. Cyburt, B. D. Fields and K. A. Olive, Phys. Lett. B 567 (2003) 227[arXiv:astro-ph/0302431].
- [6] C. Angulo et al., Nucl. Phys. A656 (1999) 3.
- [7] R. H. Cyburt, B. D. Fields and K. A. Olive, New Astron. 6 (1996) 215 [arXiv:astro-ph/0102179].
- [8] A. Coc, E. Vangioni-Flam, M. Cassé and M. Rabiet, Phys. Rev. D65 (2002) 043510 [arXiv:astro-ph/0111077].
- [9] A. Coc, E. Vangioni-Flam, P. Descouvemont, A. Adahchour and C. Angulo, Ap. J. 600 (2004) 544 [arXiv:astro-ph/0309480].
- [10] R. H. Cyburt, Phys. Rev. D **70** (2004) 023505 [arXiv:astro-ph/0401091].
- [11] P. Descouvemont, A. Adahchour, C. Angulo, A. Coc and E. Vangioni-Flam, arXiv:astro-ph/0407101.
- [12] P. D. Serpico, S. Esposito, F. Iocco, G. Mangano, G. Miele and O. Pisanti, Int. J. Mod. Phys. A19 (2004) 4431 [arXiv:astro-ph/0307213].
- [13] M. Pettini, B. J. Zych, M. T. Murphy, A. Lewis and C. C. Steidel, arXiv:0805.0594 [astro-ph], and references therein.
- [14] K. A. Olive and E. D. Skillman, New Astron. 6 (2001) 119 [arXiv:astro-ph/0007081];
   K. A. Olive and E. D. Skillman, ApJ 617 (2004) 29 [arXiv:astro-ph/0405588].
- [15] M. Fukugita and M. Kawasaki, Astrophys. J. **646**, 691 (2006) [arXiv:astro-ph/0603334].
- [16] C. Angulo *et al.*, Astrophys. J. **630**, L105 (2005) [arXiv:astro-ph/0508454].
- [17] R. H. Cyburt, B. D. Fields and K. A. Olive, Phys. Rev. D 69, 123519 (2004) [arXiv:astro-ph/0312629].
- [18] B. S. N. Singh et al., Phys. Rev. Lett. 93, 262503 (2004) [arXiv:nucl-ex/0407017];
  G. Gyürky et al., Phys. Rev. C 75, 035805 (2007) [arXiv:nucl-ex/0702003];
  F. G. Godon, J. J. J. Phys. Rev. C 77, 035805 (2007) [arXiv:nucl-ex/0702003];
  - F. Confortola et al., Phys. Rev. C 75, 065803 (2007) [arXiv:0705.2151];
  - T. A. D. Brown *et al.*, Phys. Rev. C **76**, 055801 (2007) [arXiv:0710.1279].
- [19] J. N. Bahcall, M. H. Pinsonneault and S. Basu, Astrophys. J. 555, 990 (2001) [arXiv:astro-ph/0010346].
- [20] S. N. Ahmed *et al.* [SNO Collaboration], Phys. Rev. Lett. **92** (2004) 181301

- [arXiv:nucl-ex/0309004].
- [21] A. Serebrov et al., Phys. Lett. B 605, 72 (2005) [arXiv:nucl-ex/0408009];
   A. Serebrov et al., [arXiv:nucl-ex/0702009].
- [22] S. K. Lamoreaux, [arXiv:nucl-ex/0612004];A. P. Serebrov *et al.*, [arXiv:0706.3171].
- [23] S. Nakamura, T. Sato, V. Gudkov and K. Kubodera, Phys. Rev. C 63, 034617 (2001)
  [Erratum-ibid. C 73, 049904 (2006)] [arXiv:nucl-th/0009012]. S. Nakamura, T. Sato, S. Ando,
  T. S. Park, F. Myhrer, V. Gudkov and K. Kubodera, Nucl. Phys. A 707, 561 (2002)
  [arXiv:nucl-th/0201062].
- [24] A. S. Johnson and G. M. Hale, Nucl. Phys. A688, 566c (2001).
- [25] G. Rupak, Nucl. Phys. A 678, 405 (2000) [arXiv:nucl-th/9911018].
- [26] S. Ando, R. H. Cyburt, S. W. Hong & C. H. Hyun, Phys. Rev. C 74, 025809 (2006)
  [arXiv:nucl-th/0511074].
- [27] E. G. Adelberger et al., Rev. Mod. Phys. **70**, 1265 (1998) [arXiv:astro-ph/9805121].
- [28] R. H. Cyburt and B. Davids, to be published (2008).
- [29] C. L. Bennett et al., Astrophys. J. Suppl. 148 (2003) 1; [arXiv:astro-ph/0302207];
   D. N. Spergel et al., Astrophys. J. Suppl. 148 (2003) 175. [arXiv:astro-ph/0302209].
- [30] W. Hu and S. Dodelson, Ann. Rev. Astron. Astrophys. **40**, 171 (2002) [arXiv:astro-ph/0110414].
- [31] A. Blanchard, M. Douspis, M. Rowan-Robinson and S. Sarkar, Astron. Astrophys. 412, 35 (2003) [arXiv:astro-ph/0304237].
- [32] F. Spite, and M. Spite, A.A. 115, 357 (1982).
- [33] S. G. Ryan, J. E. Norris and T. C. Beers, Astrophys. J. **523**, 654 (1999) [arXiv:astro-ph/9903059].
- [34] B.D.Fields and K.A. Olive, New Astronomy, 4, 255 (1999) [arXiv:astro-ph/9811183].
- [35] E. Vangioni-Flam, M. Cassé, R. Cayrel, J. Audouze, M. Spite, and F. Spite, New Astronomy, 4, 245 (1999) [arXiv:astro-ph/9811327].
- [36] S. G. Ryan, T. C. Beers, K. A. Olive, B. D. Fields and J. E. Norris, Astrophys. J. 530, L57 (2000) [arXiv:astro-ph/9905211].
- [37] P. Bonifacio, et al., Astron. Astrophys., 390 (2002) 91 [arXiv:astro-ph/0204332].
- [38] L. Pasquini and P. Molaro, A.A. **307** (1996) 761.

- [39] F. Thevenin et al., A.A. **373** (2001) 905 [arXiv:astro-ph/0105166].
- [40] P. Bonifacio, Astron. Astrophys. **395**, 515 (2002) [arXiv:astro-ph/0209434].
- [41] J. Melendez and I. Ramirez, Ap. J. 615 (2004) L33 [arXiv:astro-ph/0409383].
- [42] Consequences on the LiBeB elements of this temperature scale were considered in B. D. Fields,
   K. A. Olive and E. Vangioni-Flam, Astrophys. J. 623, 1083 (2005) [arXiv:astro-ph/0411728].
- [43] M. Asplund, D. L. Lambert, P. E. Nissen, F. Primas and V. V. Smith, Astrophys. J. 644, 229 (2006) [arXiv:astro-ph/0510636].
- [44] P. Bonifacio et al., A.A. 462 (2007) 951 [arXiv:astro-ph/0610245].
- [45] A. Hosford, S.G. Ryan, A.E. Garcia Perez, J.E. Norris, and K.A. Olive, submitted, 2008.
- [46] S. Vauclair, and C. Charbonnel, Ap. J. 502 (1998) 372 [arXiv:astro-ph/9802315]; M. H. Pinsonneault, T. P. Walker, G. Steigman and V. K. Narayanan, Ap. J. 527 (1998) 180 [arXiv:astro-ph/9803073]; M. H. Pinsonneault, G. Steigman, T. P. Walker, and V. K. Narayanan, Ap. J. 574 (2002) 398 [arXiv:astro-ph/0105439]; O. Richard, G. Michaud and J. Richer, Astrophys. J. 619, 538 (2005) [arXiv:astro-ph/0409672];
- [47] A. J. Korn et al., Nature 442, 657 (2006) [arXiv:astro-ph/0608201].
- [48] R. Cayrel et al., A.A. 473 (2007) L37, [arXiv:0708.3819 [astro-ph]].
- [49] D. Thomas, D. N. Schramm, K. A. Olive and B. D. Fields, Astrophys. J. 406, 569 (1993) [arXiv:astro-ph/9206002].
- [50] G. Steigman, B. D. Fields, K. A. Olive, D. N. Schramm and T. P. Walker, Astrophys. J. 415, L35 (1993).
- [51] E. Rollinde, E. Vangioni-Flam and K. A. Olive, Astrophys. J. 627, 666 (2005)
  [arXiv:astro-ph/0412426]; E. Rollinde, E. Vangioni and K. A. Olive, Astrophys. J. 651,
  658 (2006) [arXiv:astro-ph/0605633]; E. Rollinde, D. Maurin, E. Vangioni, K. A. Olive and
  S. Inoue, Astrophys. J. 673, 676 (2008) [arXiv:0707.2086 [astro-ph]]; T. Prodanovic and
  B. D. Fields, Phys. Rev. D 76, 083003 (2007) [arXiv:0709.3300 [astro-ph]]; M. Kusakabe,
  arXiv:0803.3401 [astro-ph].
- [52] V. F. Dmitriev, V. V. Flambaum and J. K. Webb, Phys. Rev. D 69, 063506 (2004)
  [arXiv:astro-ph/0310892]; A. Coc, N. J. Nunes, K. A. Olive, J. P. Uzan and E. Vangioni,
  Phys. Rev. D 76, 023511 (2007) [arXiv:astro-ph/0610733].
- [53] K. Jedamzik, Phys. Rev. D **70** (2004) 063524 [arXiv:astro-ph/0402344].
- [54] J. L. Feng, S. Su and F. Takayama, Phys. Rev. D **70** (2004) 075019 [arXiv:hep-ph/0404231];

- J. R. Ellis, K. A. Olive and E. Vangioni, Phys. Lett. B **619**, 30 (2005) [arXiv:astro-ph/0503023];
- [55] K. Jedamzik, K. Y. Choi, L. Roszkowski and R. Ruiz de Austri, JCAP 0607, 007 (2006)
  [arXiv:hep-ph/0512044]; R. H. Cyburt, J. R. Ellis, B. D. Fields, K. A. Olive and V. C. Spanos,
  JCAP 0611, 014 (2006) [arXiv:astro-ph/0608562].
- [56] D.S. Balser, T.M. Bania, R.T. Rood, and T.L. Wilson, Ap.J. 510 (1999) 759; T. M. Bania,
   R. T. Rood and D. S. Balser, Nature 415 (2002) 54.
- [57] K. A. Olive, D. N. Schramm, S. T. Scully and J. W. Truran, Astrophys. J. 479 (1997)
   752 [arXiv:astro-ph/9610039]; E. Vangioni-Flam, K. A. Olive, B. D. Fields and M. Casse,
   Astrophys. J. 585 (2003) 611 [arXiv:astro-ph/0207583].
- [58] Y.I. Izotov, and T.X. Thuan, Ap.J. **500**, 188 (1998).
- [59] T. Prodanovic and B. D. Fields, Astrophys. J. **616**, L115 (2004) [arXiv:astro-ph/0412238].
- [60] M. Zaldarriaga and A. Loeb, Astrophys. J. 562, 52 (2002) arXiv:astro-ph/0105345; P. C. Stancil, A. Loeb, M. Zaldarriaga, A. Dalgarno and S. Lepp, Astrophys. J. 580, 29 (2002) [arXiv:astro-ph/0201189].